Chronic intraaneurysmal pressure measurement: An experimental method for evaluating the effectiveness of endovascular aortic aneurysm exclusion

Luis A. Sanchez, MD, Peter L. Faries, MD, Michael L. Marin, MD, Takao Ohki, MD, Richard E. Parsons, MD, Bettina Marty, MD, Damon Soeiro, Steve Olivieri, MS, and **Frank J. Veith, MD,** *New York, N.Y.; and Watertown, Mass.*

Purpose: **To evaluate and compare the intraaneurysmal pressure (IAP) after exclusion using two different endovascular grafts.**

Methods: **Eight mongrel dogs had a 3 × 3 cm polytetrafluoroethylene (PTFE) aneurysm sewn as an interposition graft of the infrarenal aorta. A pressure transducer implanted into the aneurysm wall permitted continuous electronic IAP monitoring. Four aneurysms were excluded with a transluminally placed endovascular graft made of a PTFE graft and two Palmaz stents (PTFE-EG), three were excluded with a tantalum-Dacron endovascular graft (TD-EG), and one was surgically treated with a standard PTFE graft (PTFE-Surg). The dogs were observed for 18 to 50 days (mean, 37.5 days) and were evaluated after surgery with duplex and spiral computed tomographic scans.**

Results: **All grafts successfully excluded the aneurysms without perigraft channels or leaks as documented by arteriogram and duplex and computed tomographic scans. The mean IAPs after repair with all PTFE-EGs were significantly lower ($p < 0.001$) than the mean systemic pressures. In addition, the mean IAP reduction was significantly greater ($p < 0.005$) in the PTFE-EG group than in the TD-EG group.**

Conclusions: **Aneurysm exclusion with PTFE-EG significantly lowered IAP, did so significantly better than the TD-EG, and approached the IAP reduction obtained by standard repair. Such pressure reduction is necessary for effective protection against aneurysm rupture. (J Vasc Surg 1997;26:222-30.)**

The most significant and devastating complication of abdominal aortic aneurysms (AAAs) is rupture, and it results in more than 15,000 deaths each year in the United States.[1] The only effective treatment for AAAs is open surgical repair. Recent series have reported excellent results for elective aneurysm repair, with mortality rates lower than 5%.[2-4] This figure can be as high as 10% in some community-based settings,[5] greater than 20% for patients with severe comorbid medical conditions,[6] and even higher for patients who require emergent repair for ruptured AAAs.[2-4,7]

Endovascular grafts have the potential of successfully treating patients with AAAs with decreased morbidity rates, decreased mortality rates, and reduced treatment costs. In addition, they may be used for the treatment of high-risk patients who cannot undergo standard surgical repair. However, the effectiveness of successful endovascular graft repair in reducing the pressure within the excluded aneurysmal sac has not been clearly demonstrated.

A new animal model developed by our group[8] that allows the chronic ambulatory monitoring of intraaneurysmal pressure (IAP) was used to evaluate and compare the effectiveness of aneurysm exclusion

From the Division of Vascular Surgery, Department of Surgery, Montefiore Medical Center, The University Hospital for the Albert Einstein College of Medicine, New York; and the Boston Scientific Corporation (S. Oliveri), Watertown, Mass.

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Reprint requests: Luis A. Sanchez, MD, Division of Vascular Surgery, Montefiore Medical Center, 111 East 210th St., New York, NY 10467.

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after standard surgical repair and endovascular repair using two different devices.

MATERIALS AND METHODS

The prosthetic aneurysm model that was previously described by Faries et al.[8] was used. In summary, the fusiform arterial aneurysms (3 × 3 cm) were created by balloon dilatation of an 8 mm polytetrafluoroethylene (PTFE) prosthetic graft (W. L. Gore and Associates, Flagstaff, Ariz.), preserving 5 mm undilated segments proximally and distally for arterial anastomosis. An implantable silicon strain-gauge pressure transducer (P6.5-x6, Koningsberg Instruments, Pasadena, Calif.) was secured within the prosthetic aneurysm wall for continuous measurements of chronic IAP.

Aneurysm implantation

Eight female mongrel dogs weighing 25 to 30 kgs underwent aneurysm implantation and repair. All dogs were cared for in accordance with the "Principles of Laboratory Animal Care" (formulated by the National Society for Medical Research) and the *Guide for the Care and Use of Laboratory Animals* (NIH Publication No. 86-23, revised 1985). The dogs were initially anesthetized with intravenous sodium pentobarbital (18 to 20 mg/kg), intubated, and kept on a Harvard pump ventilator. The dog's blood pressure, heart rate, and urine output were closely monitored during the procedure.

Each dog was prepped and draped in standard sterile fashion, and 1 g cefazolin was administered intravenously before starting the procedure. A midline laparotomy incision was made. The infrarenal aorta was exposed from the renal arteries to the trifurcation. The aorta was inspected, and the 2 cm segment with the fewest branches was chosen for resection; these were ligated using 4-0 silk sutures (Ethicon, Inc., Summerville, N.J.). Heparin was given intravenously (751 U/kg), and the aorta was clamped above and below the selected site. The 2 cm segment of aorta was resected, and the prosthetic aneurysm was anastomosed as an interposition graft using CV-7 PTFE sutures (W.L. Gore) (Fig. 1). The pressure transducer cable and skin appliance were passed through a separate fascial puncture into a subcutaneous pocket lateral to the midline incision and were secured to the fascia with a 2-0 silk suture (Ethicon). The abdominal fascia was then closed with a running 0 polypropylene suture (Ethicon), and the skin was closed with a running 4-0 polyglycolic acid subcuticular suture (Ethicon). The dog was turned onto her left side to access the lower

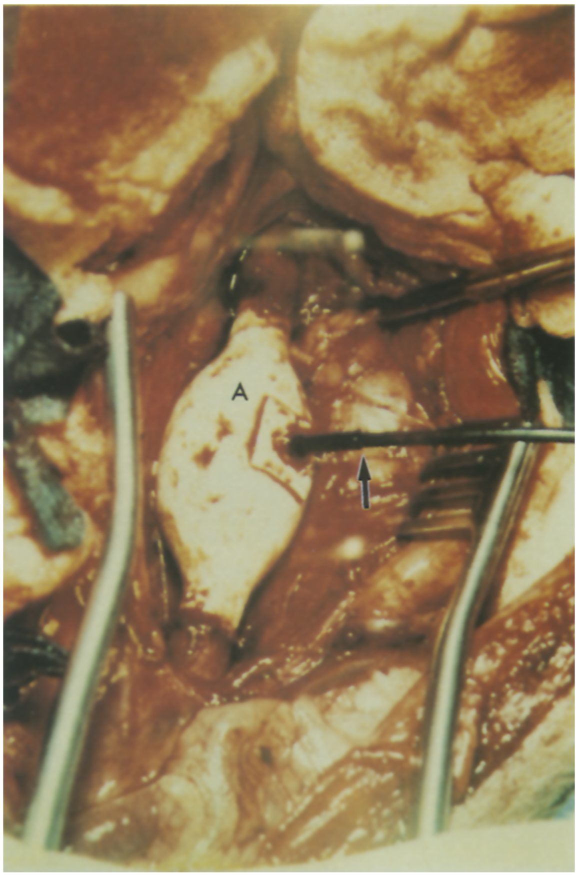

Fig. 1. Intraoperative photograph of implanted PTFE aneurysm *(A)*. Cable of pressure transducer exits to the right of aneurysm *(arrow)*.

posterior neck. A 3 cm incision was made, and a subcutaneous tunneler was advanced from the neck to the subcutaneous pocket where the transducer cable was. The skin appliance at the end of the cable was tied to the tunneler and pulled through. The skin appliance was placed through a separate stab incision and was secured to the skin with 2-0 polypropylene sutures (Ethicon). The original incision was closed with a 4-0 polyglycolic acid subcuticular suture (Ethicon).

Standard aneurysm repair

One dog underwent standard surgical aneurysm exclusion at the time of prosthetic aneurysm placement. A 6 mm PTFE graft (W.L. Gore) was inserted within the prosthetic aneurysm. The proximal and distal suture lines included the cuff of the prosthetic aneurysm and the previously inserted 6 mm graft. Subsequent blood flow was totally excluded from the aneurysm. The aneurysm cavity was filled until fully

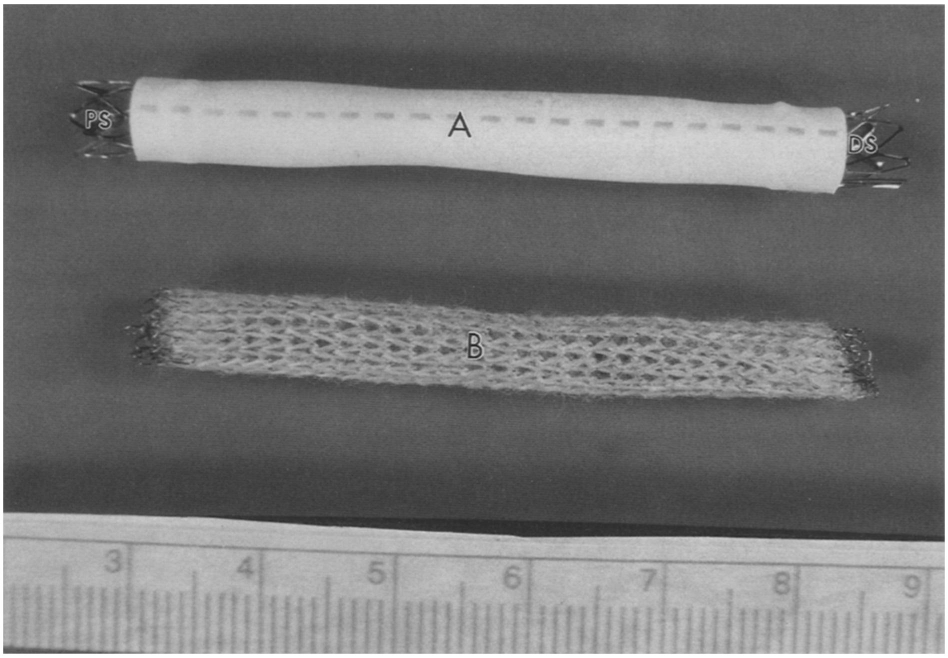

Fig. 2. A, PTFE endovascular graft was constructed by suturing one balloon expandable stent *(PS)* to the proximal end of a 4 mm PTFE graft dilated to 10 mm. After proximal stent deployment, a second stent *(DS)* was deployed to fix the distal end of the graft to the distal aorta. **B,** Tantalum-Dacron coknit endovascular graft has fenestrations of approximately 1 mm in width and 1.5 mm in length.

distended with fresh blood by injecting 20 ml of blood withdrawn from the infrarenal aorta above the implanted aneurysm.

Endovascular grafts

The remaining seven dogs underwent endovascular aneurysm exclusion 14 days after aneurysm implantation. Two different devices were used: a low-porosity PTFE endovascular graft (PTFE-EG) and a high-porosity tantalum-Dacron endovascular graft (TD-EG; Fig. 2). The PTFE-EG was 7.5 cm long and 10 mm in diameter. The graft was made by dilating a 4 mm PTFE graft (W.L. Gore) with a 10 mm Blue Max balloon catheter (Meditech, Inc., Watertown, Mass.). A 1 cm balloon-expandable Palmaz stent (P 104, Johnson and Johnson Interventional Systems, Warren, N.J.) was secured to the graft at one end using a CV-7 PTFE suture. The endovascular graft was mounted on a 10 mm × 6 cm Blue Max balloon catheter and backloaded into an 11F introducer (Meditech). The TD-EG that was used was 6 cm long and 10 mm in diameter and was mounted on a 10 mm × 6 cm balloon catheter (Meditech).

Endovascular aneurysm exclusion

The dogs were anesthetized and monitored as previously described for aneurysm implantation. A radiopaque ruler was placed behind the dog to facilitate measurements and accurate graft placement during the procedure. The neck was shaved, prepared, and draped in a sterile manner, and 1 g of cefazolin was administered. A midline neck incision was made, and the left carotid artery was isolated. Intravenous heparin (40 IU/kg) was administered, and a 14F introducer catheter (UMI Corp., Ballston Spa, N.Y.) was advanced through a limited arteriotomy. A 0.035-inch Amplatz Superstiff guidewire (Meditech) was then advanced into the infrarenal aorta under fluoroscopic control, and a diagnostic angiographic catheter (Meditech) was introduced over the wire and advanced into the distal aorta. An angiogram was obtained using 20 ml Iohexol (Omnipaque, NYCO Med Inc., DesPlaines, Ill.) to precisely localize the aneurysm. An 0.018-inch guidewire (Meditech) was advanced and the diagnostic catheter exchanged for a 5 MHz intravascular ultrasound (IVUS) catheter (Meditech). The aneurysm and the proximal and distal aorta were evaluated.

The IVUS catheter was removed. The accuracy of the chronically implanted pressure transducer was confirmed by comparing the IAP with the pressure measurements obtained from a forelimb sphygmomanometer and an intravascular manometer catheter (Miller Instruments, Houston, Tex.).

The endovascular grafts were then advanced over a 0.035-inch Amplatz Superstiff guidewire (Meditech) to the selected position, and balloon was deployed under fluoroscopic control. The proximal end of the PTFE-EG was secured first, followed by separate deployment of the distal stent with a 10 mm × 2 cm Blue Max balloon catheter (Meditech). In the dogs treated with the TD-EGs, two devices were deployed sequentially precisely overlapping each other to decrease the porosity of the device. After graft deployment, arteriographic and IVUS assessment of the endovascular graft was performed to assure accurate and complete deployment. All catheters and introducers ware removed, and the carotid artery was ligated with a 2-0 silk suture (Ethicon). The incision was closed with 4-0 polyglycolic add subcuticular sutures (Ethicon).

Assessment of endovascular exclusion

After deployment of the endovascular device, determinations of IAP were made once a day using the silicon strain-gauge pressure transducer. A forelimb sphygmomanometer was used to measure systemic arterial pressure (SP) during IAP determinations. Percent IAP reduction was calculated by using the following formula:

$$\% \text{ IAP reduction} = ([\text{SP} - \text{IAP}]/\text{SP}) \times 100$$

Dynamic computed tomographic (CT) scanning with intravenous contrast and color flow Duplex assessment of the endovascular graft were performed with the dog under general anesthesia (pentobarbital, 18 to 20 mg/kg) during the follow-up period. The dogs were killed 18 to 50 days after the aneurysm exclusion procedure (mean, 37.5 days). Microscopic and gross pathologic assessments of the endovascular graft and excluded artificial aneurysm were performed. The specimens were perfusion-fixed (pressure, 100 mm Hg) with glutaraldehyde buffered to a pH of 7.4 with sodium cacodylate. The specimens were then embedded in paraffin, and trichrome and hematoxylin and eosin slides were prepared.

Statistical analysis

Comparisons of treatment groups were performed using Student's two-tailed *t* test. Statistical significance was assumed at the 95% confidence interval ($p < 0.05$).

RESULTS

Grafting and exclusion

Endovascular device placement was successful in all dogs. Angiograms obtained at the time of the endovascular grafting procedure demonstrated complete exclusion of the aneurysm in all cases (Fig. 3). Patency of the renal and proximal lumbar arteries was assured, as was outflow into the distal aorta, trifurcation, and caudal mesenteric artery. Color flow duplex examination and dynamic CT scanning (Fig. 4) with intravenous contrast performed during the follow-up period showed no perfusion of the aneurysmal sac in all cases, confirming aneurysmal exclusion.

IAP data

Mean IAP. The mean IAP after standard surgical repair on the control dog was 12 mm Hg immediately after operation and stayed stable thereafter. The mean IAP after exclusion with the low-porosity PTFE-EG was significantly lower ($p < 0.001$) than the mean systemic pressures measured using a forelimb sphygmomanometer. In addition, the mean IAP after deploying the low-porosity PTFE-EG was significantly lower than that after deploying the high-porosity TD-EG ($p < 0.005$; Fig. 5). The mean IAP after high-porosity TD-EG was not significantly lower than the systemic pressures obtained with the forelimb sphygmomanometer.

The mean percent IAP reduction after low-porosity PTFE-EG was significantly greater than that after high-porosity TD-EG (62.0% ± 13.1% vs 13% ± 9.5%; $p < 0.005$). The mean percent IAP reduction after standard surgical repair was 88%.

Intraaneurysmal pulse pressure measurements. The mean intraaneurysmal pulse pressure after exclusion with the low-porosity PTFE-EG immediately decreased and stayed stable at a low state, whereas the placement of the high-porosity TD-EG did not significantly decrease the pulse pressure (Fig. 6). The difference in the mean pulse pressure between the two grafts were statistically significant ($p < 0.001$).

Pathologic findings

Endovascular device implantation. On gross inspection, both graft types appeared to be well incorporated into the native aorta at the proximal and distal implantation sites (Fig. 7). Histologic analysis revealed thin accumulations of smooth muscle cells and extracellular matrix within the metallic struts of

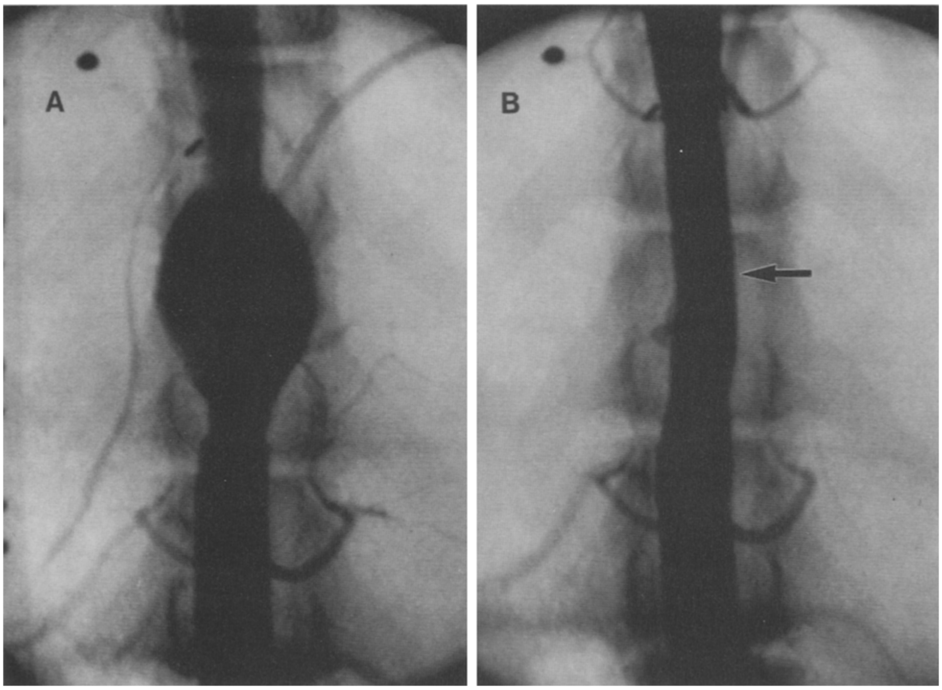

Fig. 3. A, Arteriogram shows patent infrarenal prosthetic aneurysm. **B,** Arteriogram shows complete exclusion of aneurysm by PTFE endovascular graft *(arrow)*.

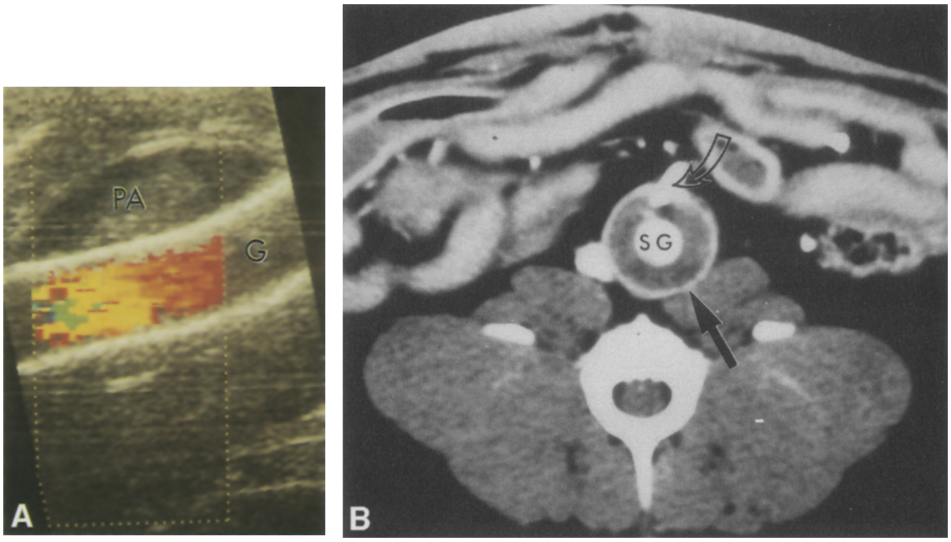

Fig. 4. A, Duplex scan shows flow within endovascular graft *(G)* and no flow within prosthetic aneurysm *(PA)*. **B,** CT scan corroborates complete exclusion of aneurysm *(black arrow)* with flow only within stented endovascular graft *(SG)*. *Curved arrow* points to pressure transducer.

each device. A layer of endothelial cells was consistently observed overlying the stents at the stent graft attachment site. However, in both grafts the midportion of the graft was not endothelialized and was covered with a thin layer of fibrin.

Intraaneurysmal thrombus. Gross pathologic examination of the aneurysms treated with the PTFE-EG demonstrated thrombus throughout the aneurysmal sac. Varying degrees of organization were present, with the outermost layers containing

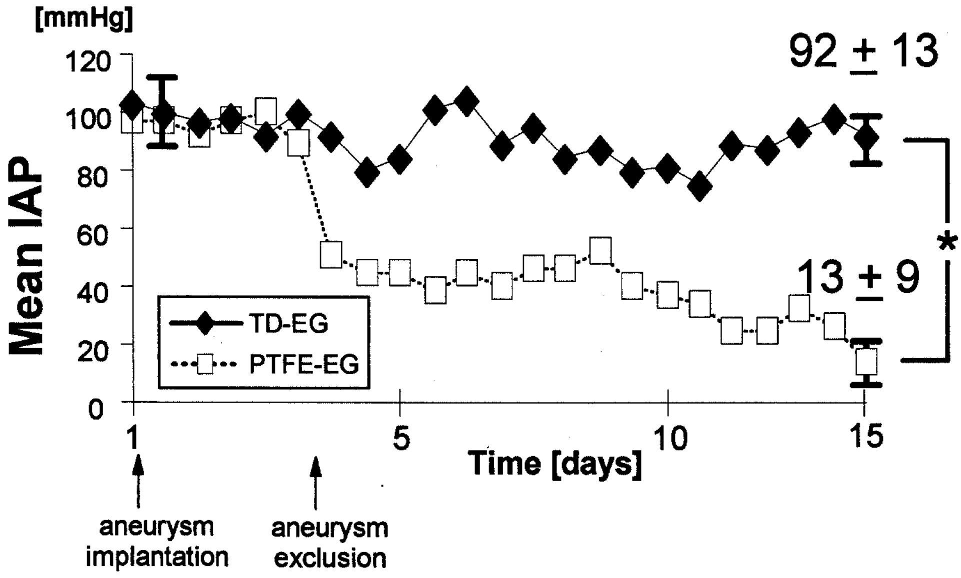

Fig. 5. Chronic mean IAP. Mean IAP after low-porosity PTFE-EG deployment was significantly lower than that after high-porosity TD-EG (*$p < 0.005$). Mean IAPs after high-porosity TD-EG were not significantly lower than preoperative IAPs.

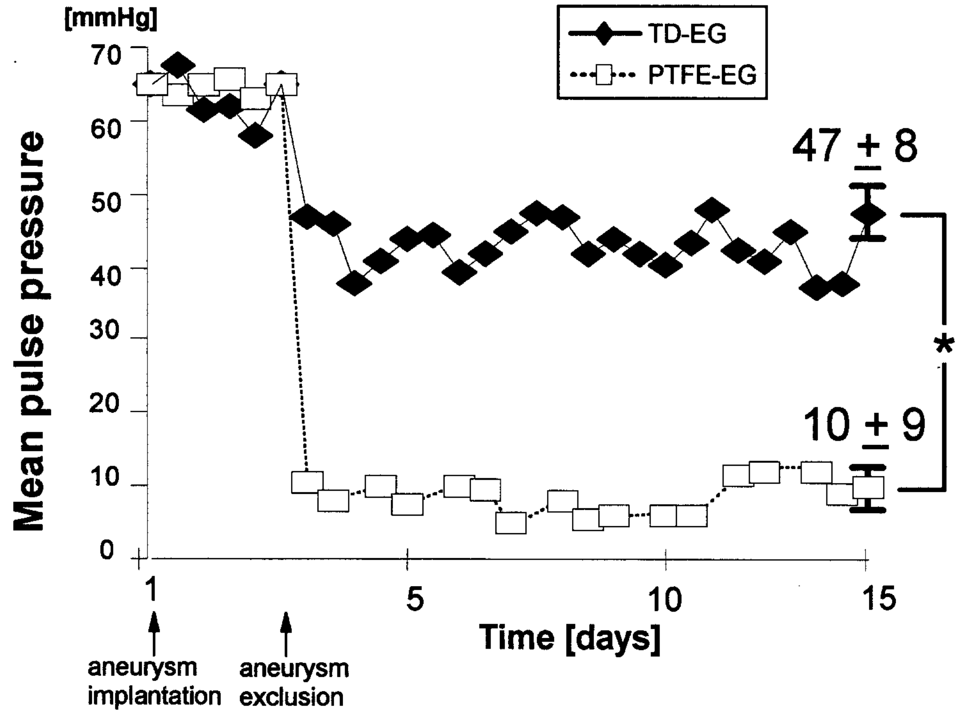

Fig. 6. Chronic intraaneurysmal pulse pressure measurements. Mean intraaneurysmal pulse pressure after exclusion with low-porosity PTFE-EG was significantly lower compared with that after high-porosity TD-EG. *$p < 0.001$.

pale, fibrinous, well-organized material. The inner layers close to the endovascular device were darker and more gelatinous, reflecting more recent deposition. Microscopic evaluation confirmed the variation in thrombus organization, with the outer layers demonstrating fibrin deposition and laminations while the inner layers had less fibrin. In contrast to the low-porosity PTFE-EG, thrombus within the aneu-

Fig. 7. Photograph of explanted aneurysm treated with high-porosity TD-EG. Graft is well healed at arterial interfaces *(A)*, and dark, rubbery thrombus *(TH)* appears relatively fresh.

rysms treated with the high-porosity TD-EG appeared to be minimally organized. The coagulum was dark, rubbery, and gelatinous suggestive of continuous blood leakage (Fig. 7). On histologic examination, poorly defined strands of fibrin were present.

DISCUSSION

A variety of devices are currently being evaluated and used clinically for the endovascular exclusion of AAAs. Stented graft devices use a vascular conduit such as Dacron or PTFE and expandable vascular stents to secure the conduit to the undilated arterial wall proximally and distally to the aneurysmal segment.[9-15] Some stented grafts use fixation pins to enhance stent attachment to the arterial wall.[16] Endovascular devices that use alloyed metals in combination with synthetic fabric throughout the length of the device are also being evaluated and used.[11,17-18] A variety of complications have been reported after endovascular treatment of AAAs. Persistent perfusion of the aneurysm sac as a result of ineffective device deployment has led to aneurysm rupture and death.[19] In addition, aneurysm expansion and rupture after technically successful endovascular graft deployment have been reported.[20] It is likely that these complications resulted from inadequate reduction of IAP. Persistent patency of the arterial side branches of aneurysms has also been observed after technically successful deployment.[17] In addition, perianastomotic reflux[15] and perigraft channels[10] with arterial flow have been noted in aneurysms after endovascular exclusion. The effects that patent side branches, perianastomotic reflux, and perigraft channels have on IAP are unclear and warrant further investigation.

Because the efficacy of endovascular devices in lowering pressure within the aneurysm sac is essential for successful aneurysm treatment and because studies have not been undertaken to chronically measure IAP after endovascular device deployment, we developed an animal model that enables us to reliably determine pressures within an aortic aneurysm before and after endovascular treatment.[8] We have used this model to assess the long-term effects of two endovascular devices.

The PTFE endovascular graft, comprised of a low-porosity PTFE graft and two balloon-expandable stents, is similar to endovascular grafts used successfully by Parodi et al.,[9,13] Marin et al.,[10] and others for the treatment of aortoiliac aneurysms. This study clearly shows that the IAP is significantly decreased within the aneurysm sac after repair using this device, and it approaches the low IAPs noted after standard repair. This study clearly shows that the IAP along with the pulse pressure is significantly decreased within the aneurysm sac after repair using this device. However, some residual pressure within the aneurysm was observed after endovascular exclusion. Although the current study supports the use of endovascular grafts for the exclusion of arterial aneurysms, the significance of the residual pressure on aneurysmal expansion is unclear, and therefore these patients need to be carefully observed. In our model, healing was noted at the interface between the stent and the proximal and distal aorta. Healing at this interface in human aortas would be helpful for long-term stability of the aneurysm repair, but the limited data about endovascular graft healing in patients treated for aortic aneurysms suggest that minimal healing occurs at these severely calcified vessels, and continued apposition of the device to the aortic wall depends on the characteristics of the attachment system used.[16]

Tantalum-Dacron grafts have been evaluated for the treatment of aortic aneurysms in an animal model.[15] The study showed that this highly porous endovascular graft was covered with a neointimal layer after 6 weeks of implantation and it appeared to effectively treat the prosthetic artificial aneurysms.[15] It has the advantage of a small profile and a simple delivery system. In our study, we confirmed that these grafts can be placed accurately across a prosthetic aneurysm and that they appear to heal very well in the perianastomotic area. In addition, all available methods used for endovascular graft evaluation, which included angiography, IVUS, duplex scan, and dynamic CT scan, showed good apposition of the graft to the arterial wall and no signs of perigraft leaks or channels. Despite the results of these studies, the IAPs after repair with the tantalum-Dacron graft were not significantly different than the systemic pressures. These findings suggest that a porous endovascular graft can promote aneurysm thrombosis and can be partially endothelialized in an animal model. However, arterial pressure is still transmitted to the aneurysm wall, rendering this type of aneurysm exclusion useless.

Angiography, duplex scanning, and dynamic CT scanning are commonly used for the postoperative evaluation of patients treated with endovascular grafts to assess the repair for appropriate placement and perigraft or endograft leaks. In our study, elevated IAPs were noted in all aneurysms treated with the tantalum-Dacron endovascular graft, despite imaging studies that suggested precise deployment and complete exclusion. The pressure transmitted to the aneurysm wall did not diminish despite the presence of thrombus occluding the graft interstices and a neointimal layer. These findings bring into question the importance of small and large perigraft leaks that are noted after endovascular repair that "seal spontaneously." Our findings may help explain why some aneurysms have been noted to enlarge or even rupture when an endovascular graft appears to totally exclude an aneurysm. In addition, the development of new diagnostic tests may be needed to better evaluate and observe patients after endovascular aneurysm repairs.

CONCLUSION

Although standard surgical repair of AAAs has proven to be clinically effective in preventing rupture, it can be associated with significant perioperative morbidity and mortality rates, particularly in patients with comorbid illnesses. Recently developed techniques for the endovascular treatment of AAAs may reduce the morbidity and mortality rates of aneurysm repair. However, the effectiveness of these techniques must be rigorously evaluated. Our model may be used to reliably evaluate the ability of current and future endovascular devices and delivery systems to reduce IAP after deployment. Insight into existing questions, such as the importance of perigraft channels, efficacy of different types of endovascular grafts, and future questions associated with endovascular graft repairs, can be obtained from future studies using this model.

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